Studying the Sense of Embodiment in VR Shared Experiences

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Figure 1: Setup of the experiment: each user was able to interact in the virtual environment with his own avatar, while the physical setup provided both a reference frame and passive haptic feedback. From left to right: experimental conditions Alone, Mirror and Shared; Physical setup of the experiment.

Abstract

In this paper, we explore the influence of sharing a virtual environment with another user on the sense of embodiment in virtual reality. For this aim, we conducted an experiment where users were immersed in a virtual environment while being embodied in an anthropomorphic virtual representation of themselves. To evaluate the influence of the presence of another user, two situations were studied: either users were immersed alone, or in the company of another user. During the experiment, participants performed a virtual version of the well-known whac-a-mole game, therefore interacting with the virtual environment, while sitting at a virtual table. Our results show that users were significantly more "efficient" (i.e., faster reaction times), and accordingly more engaged, in performing the task when sharing the virtual environment, in particular for the more competitive tasks. Also, users experienced comparable levels of embodiment both when immersed alone or with another user. These results are supported by subjective questionnaires but also through behavioural responses, e.g. users reacting to the introduction of a threat towards their virtual body. Taken together, our results show that competition and shared experiences involving an avatar do not influence the sense of embodiment, but can increase user engagement. Such insights can be used by designers of virtual environments and virtual reality applications to develop more engaging applications.

Index Terms: Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 Introduction

With the development of consumer-grade Virtual Reality (VR) equipment, more and more high-quality shared VR experiences are now being released by VR developers. Such progresses reinvigorate research interests in shared virtual environments (VE), e.g. [6, 17, 35], and therefore in exploring the questions raised by such experiences. How do people interact with each other in VR? How do we represent users in VR? How do users perceive their virtual representation in VR? How does this representation influence their virtual experience?

Among these topics, questions related to the avatar (i.e. the user's representation in the VE) are becoming more and more important because of their potential influence on shared experiences, especially as avatars have been demonstrated to improve perception in VR [22], to influence behaviour [25], and to provide a certain level of embodiment in the virtual world [15]. In particular, the notion of Sense of Embodiment (SoE) is becoming more and more exploited to evaluate the extent to which users claim ownership of their avatar, e.g., to demonstrate that a virtual limb or a full virtual body can create illusions of body ownership [37,40], even to the extent of controlling virtual bodies differing from the participants' own body [12, 46]. However, such studies only focus on single-user experiences. It is therefore unclear how sharing virtual experiences with another user embodied in an avatar might influence one's own SoE, which is the focus of this paper.

At this point, it seems important to mention the concept of Presence in VR, which has been widely studied for shared experiences (e.g., [10,33]). Particularly related to this paper, it was demonstrated that the sight of a human-like representation in the VE (apart from user's own avatar) had a positive effect on users' sense of presence [44]. However, Presence focuses on "the feeling of being in the virtual world" [34], and not specifically on "the feeling of being embodied in one's avatar" [15], and therefore differs from the SoE. This is why we focused in this paper on the SoE and decided to evaluate if the presence of other users embodied in the VE influences a user's own SoE.

To explore this question, ten pairs of male participants volunteered for a VR experiment where they sat in front of a table, with co-localized physical and virtual setups. They were embodied in a co-localized avatar (see Figure 1) and were asked to perform a gamified task. Each participant performed the experiment both alone and facing another embodied user. In order to assess users' SoE, we collected subjective questionnaires during and after the experiment, as well as physical reactions to the presence of a visual threat introduced in the form of sharp spikes at the edges of the table in half of the experimental conditions. Our results show that users experienced comparable levels of embodiment when immersed alone or with another user, but were more engaged when sharing the

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virtual experience, in particular during more competitive tasks. In this paper, the term "engagement" is related to the user implication and involvement in the VE, which was suggested to be strongly influenced by the notion of embodiment [30].

The remainder of the paper is structured as follow. Section 2 provides an overview of related work regarding the SoE and shared experiences in VR. Section 3 presents the experiment conducted to evaluate the SoE in shared experiences along with the results, which are discussed in Section 4. Finally, Section 5 provides the concluding remarks.

2 Related Work

2.1 Embodiment in VR

With the recent technological developments, avatars are now highly used in VR for research purposes, e.g., for 3D graphics and games research [43], behavioral research in psycholinguistic [11], or psychological research in general [47]. Indeed, avatars can be altered in numerous ways to assess changes in users' behaviors. It becomes possible to control the realism [26], the shape [28] or even the morphology of the avatar [12]. But how can the effects of these changes be measured? As mentioned by Jacquelyn Ford Morie, when a user enters a VE, he has the simultaneous perception of two distinct bodies *"whether there is a virtual body image or whether there is direct or interpreted mappings of navigation movements"* [23]. However, we can wonder if it is possible to experience the same sensations across a virtual body in an immersive VE as we would experience them through the biological body. This can be measured by studying the SoE, a complex phenomenon which can be further subdivided in three dimensions according to Kilteni et al. [15]: the sense of self-location, the sense of agency and the sense of body ownership. While De Vignemont [7] also provided a similar division by three main dimensions (Spatial, Motor and Affective), we decided to use the definition of Kilteni et al. in our study.

Self-location - *"The sense of self-location refers to one's spatial experience of being inside a body and it does not refer to the spatial experience of being inside a world"* [15]. How do we perceive ourselves located in a virtual space? What can alter this sense of self-location? Among other studies, the famous rubber-hand illusion experiment [5] revealed that the sense of self-location can be modified when synchronous visuo-tactile correlations are applied to a fake (rubber) and a real hand. This experiment has also been extended to virtual reality [37] increasing the possibilities to elicit a sense of embodiment by a more flexible approach, with for example the possibility to easily move the virtual arm according to the participant's movements.

Agency - The sense of Agency can be described as a motor activity control, and refers to the fact of experiencing an action, intention or selection toward a body. When proprioception is defined as the sense *"that people know where the parts of their body are"*, the sense of agency could be defined as the sense that people have of knowing which action they can do, which control they have over this body and to which extent [4]. For example, it was questioned whether the virtual representation of a hand alters the sense of agency [2], which was demonstrated to be more related to the virtual hand control and the task efficiency than to the virtual hand representation.

Ownership - The sense of ownership can be described as one's self-attribution of a body [1] and a number of studies have explored how ownership can be elicited. For example, Botvinick et al. [5] showed that synchronous visual and tactile stimuli can elicit the illusion of the ownership of a fake limb (rubber hand) into one's body representation. However, most studies only manipulate a limited number of factors. According to Slater et al. [40], the power of immersive virtual reality (IVR) had not been exploited yet to create various transformations in body ownership. Indeed, IVR gives the possibility to another kind of experimental design which allow to easily test different factors, such as first person point of view (1PPOV) to third person point of view (3PPOV) [27], changing the visual aspect of a part of the virtual body [46] or altering the morphology of the virtual body [12, 18].

2.2 Evaluating VR Shared Experiences

As people commonly interact and collaborate with each other in real life, the need to enable such collaborations to create more immersive VR is nowadays increasing. Historically, such questions paved the way to the development of Collaborative Virtual Environments (CVEs) [35], telepresence platforms, and led to several types of experiments, e.g., regarding social interaction and group behavioral studies [41]. For instance, multi-user immersion was used to evaluate whether users in a small group would be more efficient in realizing a task in real world or in virtual reality [39], with results suggesting that the immersed person tended to emerge as the leader in virtual groups, but not in real meetings.

To evaluate and enhance the quality of such shared experiences, the concept of Presence was originally explored. However, because of the complexity of such experiences, a user's sense of presence can be influenced by numerous factors [34]. In particular, it was demonstrated that seeing other users in the VE could be taken as an evidence of one's proper existence in the VE, and could increase the sense of presence [10]. This supported the necessity to differentiate new notions, such as co-presence and social presence, from personal presence [36]. Those terms became highly employed when conducting studies on CVEs, for example in [29]. It is indeed quite interesting to wonder how being with others in the same VE might influence the way we perceive it. It was for instance showed in [38], that co-presence in VR has for consequence to amplify users' reaction, making a "bad" situation worse and a "good" situation better.

Following these results, several studies naturally focused on the effects of the user representation on the sense of presence in shared VEs. In particular, they demonstrated that embodying users in anthropomorphic and realistic avatars also increase their own sense of presence [24], and more generally enhance their whole VR experience [3, 32]. For instance, it was demonstrated that changing the avatar representation had a direct effect on the quality of social interaction in shared VEs, and more precisely that social interactions tend to be impeded with non-realistic avatars [31].

However, while measuring the quality of VR shared experiences with multi-user immersion has clearly required to explore new concepts related to the sense of presence, such as co-presence and social-presence, the sense of embodiment which is widely studied for single-user experiences is seldom explored in this context. For this reason, our contribution in this paper is to explore the influence of sharing a VR experience on the sense of embodiment.

3 Experiment

We hypothesized that being immersed in the same VE while sharing a common task together with another user will reinforce the SoE. In particular we made the assumption that seeing another user's avatar will reinforce the user experience, and in particular, that it will enable users to experience a higher sense of ownership and agency. In order to test this hypothesis, we designed an experiment in which users could perform a specific task, i.e. a whac-a-mole game (see Figure 1), alone or together with another user. To ensure that potential differences would not only be due to additional visual cues due to the presence of another body, we also introduced a condition where users were immersed alone in front of a mirror and therefore saw their own reflection. In order to assess users' SoE, we collected subjective questionnaires during and after the experiment. We also introduced a visual threat in half of the trials, in the form of sharp spikes at the edges of the table, and measured users' behavioral changes while performing the task.

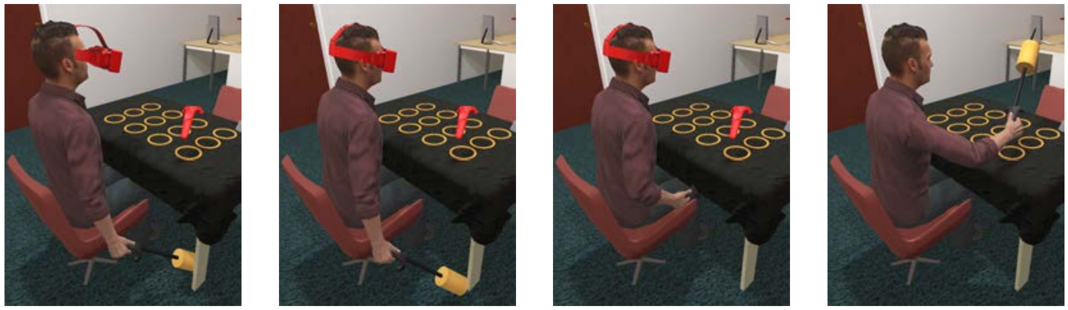

Figure 2: Main steps of the Inverse Kinematics based avatar animation. The physical position and orientation of the Vive HMD and controllers are displayed in red, and used as targets for our IK method. Steps are in order: 1) avatar initial resting pose, 2) rotation of the torso to align the avatar's head with the HMD, 3) elbow flexion to satisfy the distance between the shoulder joint and the target wrist (inferred from the controller transformation), and 4) final pose after rotating the shoulder to align the wrist with the target wrist.

3.1 Participants

Twenty male unpaid participants from the university campus took part in the experiment (age: min=21, max=33, and avg=26$\pm$2), recruited both among general students and staff. They were all naive with respect to the purpose of the experiment, had normal or corrected-to-normal vision, and gave written and informed consent. The study conformed to the declaration of Helsinki. Participants took part in the experiment in pairs. Among the participants, 9 subjects had none to very limited previous experience with VR, 6 had some previous experience, and 5 were familiar with VR. All participants were right-handed male Caucasians, to match the visual appearance of the virtual avatar as much as possible. In order to avoid any gender interaction bias, we always used same-gender avatars for each participant pair, with the assumption that mixing genders in pairs could have influenced interaction between users.

3.2 Technical Details

We developed a collaborative platform in Unity in which two users could share the same virtual and real environment, and interact in real time. Our setup was based on two HTC Vive Head-Mounted Displays (HMDs) with four HTC Vive controllers, to immerse participants in the VE. Users were embodied in anthropomorphic virtual avatars in 1PPOV (see Figure 4 left). In the center of the tracking zone, two chairs and a table were placed. A thin foam layer covered the table to avoid impacts of the HTC Vive controllers. The physical furniture had its virtual counterpart in the VE providing both a reference frame and passive haptic feedback (see Figure 1). Finally, the experiment took place inside a standard virtual office.

In order to elicit high levels of embodiment, we chose to use realistic human avatars in our experiment. Because sharing experiences with other embodied users means that people do not only observe their own virtual body, but also others', a lot of attention was given to the animation quality of the avatars, i.e. on the way avatars moved according to their user's movements. In particular, animation and control quality are strongly linked to the sense of agency, and are therefore extremely important to measure the SoE. We then detail two main aspects of the animation of the avatars: 1) the calibration of the avatar size to the user's and 2) the animation of the avatar according to the user controls (i.e. HTC Vive head and hands tracking).

3.2.1 Avatar Calibration

In order to provide the best experience, it is important to match the participants' height with their avatar's, in particular to ensure that the camera viewpoint is located near the head of the avatar, and at a correct height from the floor. Before starting the experiment, participants were therefore asked to sit upright on their chair while wearing the HMD and to place their hands on the table while holding the controllers. Then, the avatar's torso was automatically scaled to align the vertical position of the HMD with the avatar's eye height.

3.2.2 Avatar Animation

Avatars were controlled by user movements through the use of the HTC Vive HMD (head) and controllers (hands). However, as users were sitting in a chair, we only needed to animate the upper part of the avatar body, which was performed using a two-step process. First, we used the HMD position to drive the torso of the avatar by rotating the torso (from spine to head) around the pelvis (Figure 2.2), thus ensuring the alignment of the HMD position with the avatar's eyes (i.e. leaning based on the user's movements). Yet, during pilot studies we noticed that such alignment was not sufficient when users looked behind them, which often occurs when users want to explore a new virtual environment. As shoulders were not tracked, only the head of the avatar turned in such cases, which created visual skinning artifacts around the neck. As real life people would actually twist their spine to look behind them, we therefore included an additional linear combination of the head rotation along the spine which minimized skinning artifacts.

As a second step, the arms of the avatar were then driven with a standard analytical Inverse Kinematics method using the position and orientation of the Vive controllers. The rig of the character hands were modified ensuring that the character grasped the controller as naturally as possible. As the character rig and the current position and orientation of the controllers were known, the position and orientation of the characters' wrist could be inferred (hereafter referred as target wrist). At that stage we make two assumptions: first that the predefined relative transformation locating the Vive controller in the hand coordinate system is the same for all subjects and second, that it remains constant during the experiment, i.e. subjects do not modify their initial controller grasping posture. This approach provided satisfying results.

Moreover, characters were manually posed at rest (before animation) with the arms at a 10° abduction angle from the vertical of the trunk (see Figure 2.1). During run-time, forearms were first flexed so that the distance between wrist and shoulder joints matched the distance between the shoulder joint and the target wrist (Figure 2.3). Then, we computed the normal vector to the plane defined by the shoulder, wrist and target wrist positions, and rotated the arm around this vector to align the wrist with the target wrist (Figure 2.4). This method allows us to avoid elbow singularities, while creating arm poses driven by the original abduction angle of the avatar at rest. While the elbow location might not match the users', this is a solution commonly used in interactive applications [16] [9]. It is also important to point out that the avatars' static hand postures matched a natural grasping of the virtual HTC controllers. We address the reader to the accompanying video to appreciate the avatar animation.

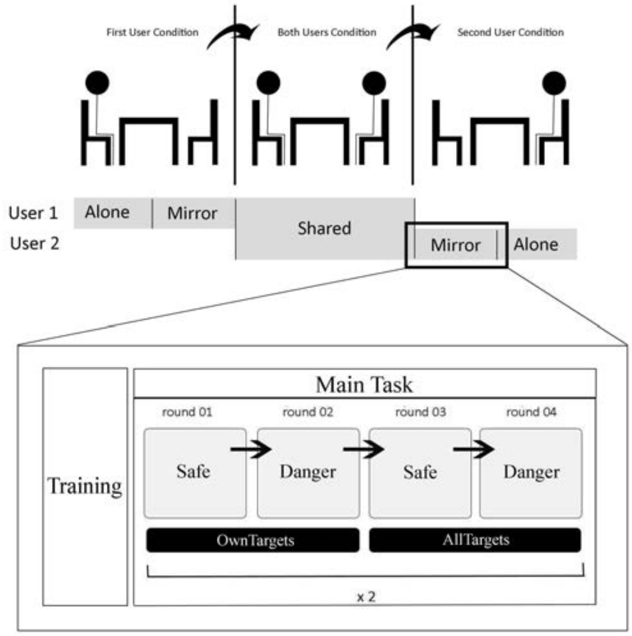

Figure 3: (Top) Experiment organization for each pair of users, according to the three conditions: Alone, Mirror, Shared. Alone or Mirror conditions were randomly presented first. (Bottom) Details of each condition organization: training followed by the main task, where OwnTargets or AllTargets were presented in random order. Danger and Safe stages were also presented in random order.

Figure 4: 1PPOV when performing the whac-a-mole task (left) and 3PPOV when performing the Training (right).

Figure 5: Danger: virtual spikes appeared around the virtual table in order to threaten the virtual body.

3.3 Experimental Protocol

Upon their arrival, participants read and signed the experiment consent form and filled in a demographic questionnaire. Then, they were briefed about the experiment and immersed into the VE (occupying one of the two chairs). As some experimental conditions (see Section 3.4) required one user and others two users, we scheduled the experiment so that 1) the first user performed all single-user conditions, then 2) the second user arrived and the two-users conditions were performed, and finally 3) the first user left and the second user performed the single-user conditions (see Figure 3).

Before each condition participants performed a short training session, in which they were asked to grasp virtual cubes and to place them at specified locations to become familiar with the system and the environment (see Figure 4 right). Using the original 3D model of the HTC Vive controller, we attached a 3D claw model on top, which was animated when pressing the trigger button of the controller. The virtual claw was used to pick up the cubes and to move them. When two users shared the same environment, they performed this task together by positioning successively one cube at a time.

After the training, participants performed the main task which consisted in a whac-a-mole game. A virtual foam hammer was attached to the virtual HTC Vive controller of the user's dominant hand, which participants used to hit the moles. Moles appeared at random time intervals and at random spots on the table (4x3 spots), and stayed visible from 0.8 to 2.6 seconds. They were also color-coded to indicate to participants which moles they had to hit (see Section 3.4). A score panel displayed the accumulated score for each round. Hitting the right mole increased the score by one, and hitting a wrong mole decreased the score by one. The task was moderately demanding in terms of attention and required fast reaction. Furthermore, while the non-dominant was not actively used in the task, users were still holding a controller tracking their non-dominant hand location. This information was used both for analysis of embodiment and animation purposes. Finally, participants filled in a subjective questionnaire at the end of each block of the experiment in order to gather subjective impressions on presence and embodiment.

3.4 Experimental Design

In our within-subject design, three independent variables were considered: Experience, Target and Danger. The main independent variable (Experience) considered whether there was a shared experience or not, and had three levels (Figure 1): 1) the user performed the task alone (*Alone*), 2) two users performed the task at the same time, sitting in front of each other (*Shared*), and 3) a control condition in which the user performed the task alone, but a mirror in front of him enabled to see his avatar (*Mirror*). The second independent variable (Target) was the difficulty of the whac-a-mole task, which had two levels: 1) users could hit all the moles (*AllTargets*) and 2) users could hit only half of the moles (*OwnTargets*). In *OwnTargets*, users were asked to hit only the moles corresponding to their color (matching the color of their shirt, green or purple), and hitting the wrong mole decreased their score. In *AllTargets*, all moles had the same color (white). This variable allowed to create two different situations. One more competitive, where users had to compete for the same moles, and another less competitive, where they only focused on their moles. Finally, the addition of potentially harmful elements in VEs is commonly used in embodiment studies to assess behavioral responses [12, 47]. Thus, we considered the additional independent variable (Danger) whether there was a potential threat to the virtual avatar (*Danger*) or not (*Safe*). The potential threat were 25cm-height sharp spikes placed around the table (Figure 5).

The overall organization of the experiment is summarized in Figure 3, and further described below. The experiment was divided into 3 blocks, corresponding to the three Experience conditions. The Experience conditions were not fully-counterbalanced due to practical reasons, as single conditions were always done together.

Yet, half of the users did the shared condition first and half did it last. The Alone and Mirror conditions were counterbalanced for each pair of users. Each block included the training task and eight rounds of the whac-a-mole task (2 Target x 2 Danger x 2 repetitions). Each round had a duration of 1 minute and the threat always appeared 3 seconds after the beginning of the round and remained present until the end of the round. Target and Danger levels were fully counterbalanced. There were 32 moles for each round. At the end of each block, users removed the HMD and filled a subjective questionnaire to gather their subjective impressions. In total the experiment lasted approximately one hour.

The measured data (dependent variables) took into account performance and behavioral measurements which might show changes on the sense of embodiment (mainly ownership). Regarding performance, we only measured the mean *selection time*. It considered the time required to hit the mole after its appearance (in seconds). For each user, only trials in which they successfully hit a mole were considered. We did not consider the user score because performance was close to 100% in most conditions. Regarding behavioural measures, we mainly focused on the mean elevation of the dominant and non-dominant hands (in meters), which could be influenced by the virtual threat. Finally, there is also the subjective responses for the final questionnaire (see Table 1). The questionnaire was inspired from previous work [5, 14, 20] and divided in three groups: presence, ownership and agency. For each question, participants were asked to rate their answer on a 7-point Likert scale. Participants also reported general comments and feedback at the end of each questionnaire.

In summary, considering our experimental design, our main hypotheses were:

H1 The more competitive the task is, the lower the mean selection time will be.

H2 The mean elevation of the dominant hand will be higher when the Danger is visible.

H3 The mean elevation of the non-dominant hand will be higher when the Danger is visible.

H4 Presence ratings will be higher when sharing the VE.

H5 Body ownership ratings will be higher when sharing the VE.

H6 Agency ratings will be higher when sharing the VE.

3.5 Results

Three-way Repeated Measures ANOVA analyses were performed to test the significance of the Experience, Danger and Target levels for each dependent variable. When main or interaction effects were found ($p < 0.05$), they were explored using pairwise Tukey post-hoc tests ($\alpha > 0.05$). Only significant results are discussed. Anderson-Darling normality tests were performed to ensure a normal distribution of the data. Effect size was computed using partial eta squared (η_p^2).

Selection Time: The ANOVA analysis showed three main effects regarding Experience ($F_{2,32} = 47.31$, $p < 0.001$, $\eta_p^2 = 0.75$), Danger ($F_{1,16} = 22.08$, $p < 0.001$, $\eta_p^2 = 0.58$) and Target ($F_{1,16} = 232.46$, $p < 0.001$, $\eta_p^2 = 0.94$), Figure 6 (Left) shows the summary of the results. Post-hoc tests showed that participants were significantly faster in the Shared condition compared to the Alone or the Mirror conditions. They were also significantly faster in AllTargets compared to OwnTargets, as well as in the Safe compared to Danger stages. Furthermore a two-way interaction was found between Experience and Target ($F_{2,32} = 35.75$, $p < 0.001$, $\eta_p^2 = 0.69$), where post-hoc tests showed that users were the fastest in the Shared $\times$ AllTargets combination. The interaction effect supports **H1**, as the most competitive condition Shared $\times$ AllTargets had the lowest selection time. **H1** is further supported by the main effects of Experience and Target.

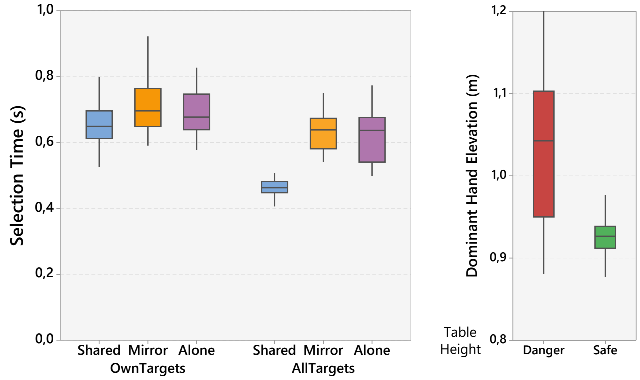

Figure 6: Results summary. (Left) Boxplot of the selection time grouped by Target and Experience. (Right) Boxplot of the dominant hand elevation when hitting the mole grouped by Danger.

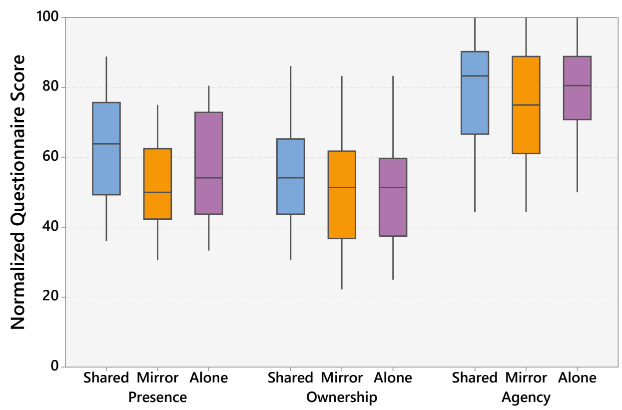

Figure 7: Boxplot of questionnaire ratings for presence, ownership and agency, grouped by Experience.

Dominant Hand Elevation: The ANOVA analysis only showed a main effect of Danger ($F_{1,16} = 33.18$, $p < 0.001$, $\eta_p^2 = 0.67$). Post-hoc tests showed that users placed their dominant hand higher when the danger was visible than when it was not ($M = 1.03m$; $SD = 0.08m$ vs $M = 0.93m$; $SD = 0.04m$; table height: 0.8m; see Figure 6, Right). This result supports **H2** and showed an adaptation of users' behaviour due to the appearance of the virtual spikes.

Non-Dominant Hand Elevation: The ANOVA analysis showed a main effect of Experience ($F_{2,32} = 11.03$, $p < 0.05$, $\eta_p^2 = 0.19$) and a two-way interaction effect between Target and Danger ($F_{1,16} = 10.61$, $p < 0.01$, $\eta_p^2 = 0.4$). However, post-hoc tests did not show any significant effect, and mean differences were not higher than a few centimeters overall. The mean elevation was $M = 0.81m$; $SD = 0.05m$ which shows that it remained very close to the height of the table (0.8m). In summary, this result does not support **H3**.

Questionnaires: Data from the questionnaires was structured into three groups (presence, ownership and agency). For each group and user, the scores were added (control questions were included by inverting their score), and normalized between 1 and 100 to improve readability (see Figure 7). In order to enable the analysis of the interaction effects (mixed ANOVA analysis) due to the non-continuous nature of the data, unaligned rank transform [45] was applied. The ANOVA analysis considered the within-subjects variable Experience and the between-subjects variable Order (Shared first vs Shared last). Regarding presence, the ANOVA showed a main effect of Experience ($F_{2,32} = 8.56$, $p < 0.001$). Post-hoc tests showed that the overall

Table 1: Questionnaire used in the experiment.

Variable	Question
Presence	- Please rate your sense of being in the virtual office space, on the following scale from 1 to 7, where 7 represents your normal experience of being in a place. I had a sense of "being there" in the virtual office space - To what extent were there times during the experience when the virtual office space was the reality for you? There were times during the experience when the office space was the reality for me... - When you think back about your experience, do you think of the office space more as images that you saw, or more as somewhere that you visited? The office space seems to me to be more like ... - When you think back about your experience, do you think more as being elsewhere, or more as being in the office space? I thought more as... - Consider your memory of being in the office space. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By 'structure of the memory' consider things like the extent to which you have a visual memory of the office space, whether that memory is in colour, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements. I think of the office space as a place in a way similar to other places that I've been today... - During the time of the experience, did you often think to yourself that you were actually in the office space? During the experience I often thought that I was really seated in the office space...
Ownership	- I felt that the virtual body was my own body. - I felt that the virtual arms were part of my body. - I felt that the virtual arms could be harmed. - I felt that my real arms could be harmed. - I felt that virtual arms were not part of my body. - I felt as if the virtual arms were from someone else's body.
Agency	- I felt as if the virtual body moved just like I wanted it to, as if it was obeying my will. - I expected the virtual body to react in the same way as my own body. - I felt like I controlled the virtual body as if it was my own body.

sense of presence was higher for the Shared condition compared to the Mirror condition ($p < 0.05$) and also for the Alone condition ($p < 0.05$). This result supports **H4**. Regarding ownership, an interaction was found between Experience and Order ($F_{2,32} = 5.35$, $p < 0.01$), which was not confirmed by the post-hoc analysis. Still, a deeper analysis seems to suggest that participants who started with the Shared condition gave a lower ownership score for the Alone and Mirror conditions compared to the users finishing with the Shared condition. Yet, the results are inconclusive and do not support **H5**. Finally, for agency the ANOVA showed a significant main effect of Experience ($F_{2,32} = 3.63$, $p < 0.05$). Post-hoc tests showed that agency ratings were lower for the Mirror condition compared to the Shared condition ($p < 0.05$). This result does not support **H6**.

4 Discussion

The main objective of the experiment was to evaluate the influence of sharing a VE with another user also embodied in an avatar on each other's SoE. In this Section we discuss how the results can be interpreted in terms of body ownership and agency but also provide additional insights regarding user engagement and presence. We further illustrate those results with written user feedback, either supporting our results analysis or highlighting other aspects that did not arise from the variables observed during the experiment.

4.1 User Performance and Engagement

The results on selection time show that users were significantly more "efficient" in performing the task when sharing the VE and in particular in the competitive level (AllTargets). First, the main effect of Target shows that participants required less time to select the targets in the AllTargets level vs the OwnTargets level. This result can be explained by the increased cognitive load for the OwnTargets level as users had to determine whether the target had to be selected or not. Second, the main effect of Experience could be explained by an increased user engagement during the competitive (Shared) condition, leading to decreased selection times. In particular, this effect was stronger in the AllTargets level (significant interaction effect). This explanation is supported by Lalmas et al. [19] who stated that user engagement depends on time, and that challenge is an element that influences engagement.

Moreover, it is important to highlight that when users had to compete for the same moles, the evaluated selection time is actually the best out of two participants, rather than their individual performance. Despite the fact that selection time was significant lower in the Shared condition compared to the other conditions, it is still possible that this observation could have influenced this result. However, our result is also supported by the other subset of trials where users had to hit their own moles, in which a relevant change in the selection time was also observed depending on Experience, a result also supported by the increased presence ratings in the Shared condition.

User feedback was also in line with this interpretation. Users expressed a positive feeling towards the fact of sharing the VE with another user: *"This is more enjoyable and realistic with a partner"*, *"The feeling of incarnating the avatar is globally better with a second user in front"*, or *"It is better with another person during the experiment"*.

Finally, users were also faster when the danger was not displayed. While it is difficult to separate selection time from the fact that their dominant hand was closer to the table in the Safe stage, or from the fact that they might have been more careful in the Danger stage, it is nonetheless important to take into consideration that users displayed different "motor strategies".

4.2 Body Ownership

First of all, subjective results on body ownership did not show any significant differences at the level of Experience. On average, participants reported a medium level of body ownership $M = 52.0$; $SD = 15.7$. Yet, participants starting with the Shared condition demonstrated a tendency to report lower ownership ratings for the Alone and Mirror conditions. This suggests that the Shared condition might have provided an upper bound sense of ownership depending on whether users started with the Shared condition or not. Nevertheless additional experiments would be required to validate this assumption.

Regarding the behavioural measurements, we found that participants placed their dominant hand higher in the presence of a virtual threat. Several hypotheses may explain this phenomenon: is this reaction due to the fact that they feared the threat? Or is it just because they avoided the collision? As it is established that a response to a threat testifies of a high sense of ownership, we make the assumption that participants were really punctually afraid for their virtual body to be harmed. On the contrary, it appeared that participants nearly did not raise their non-dominant hand when the threat was introduced, independently of the condition tested. It is however unclear why participants would react to a threat with their dominant-hand and not with their non-dominant hand. As participants did not need to interact using their non-dominant hand, it is therefore possible that this absence of interaction could be a reason why participants seemed to less appropriate their non-dominant virtual hand as their own. It is also possible that the non-dominant hand was less present in the field of view of participants, which could have influenced their reaction. In either way, participants were never asked to maintain their non-dominant hand on the table. This observation opens the question whether body ownership is uniform regarding the entire virtual body, or depends on whether a body part is active or not.

In addition, comments from users also testified of a reaction toward the virtual threat: *"I felt strange when I moved my arm through the spikes"* or *"When the table was surrounded with spikes, it took me several seconds to be at ease with them and realize I could not be harmed"*. These remarks support the results of the dominant-hand height regarding the sense of ownership towards the virtual body. It has been considered the possibility that participants would actually move their hand thinking that touching the spikes would decrease their score, as the game was quite competitive, but the way most participants quickly reacted, surprised by the danger appearing, testifies of a basic instinct to a threat toward their body.

It is also interesting to acknowledge that we did not observe a significant increase in ownership in the mirror condition, which is contradictory to previous work where the presence of such a mirror was found to enhance the sense of ownership [8, 42]. One possible explanation is that the mirror might have been distracting for participants, and have possibly highlighted small animation artifacts, which was however not reported by any participant. Furthermore, this result can also be explained due to the uncanny valley effect [21]. The choice of a realistic anthropomorphic avatars might have influenced how participants accepted the avatar as their virtual representation, which could be further explored in future experiments.

4.3 Agency

Overall the agency score was high ($M = 78.09$; $SD = 15.24$), which shows that the avatar control was realistic and efficient. We took great care in providing a high quality to the visual rendering of the virtual scene, both in terms of appearance and avatar animation. Users were immersed in a realistic environment, similar to a real office, and embodied in realistic anthropomorphic avatars.

Interestingly, the analysis of Agency scores showed that the levels of agency were lower for the Mirror condition. Indeed, three participants communicated a negative feeling towards the presence of a mirror in the VE: *"It is better without the mirror"*, *"The mirror effect creates a loss of the sense of presence, I couldn't say why, but it installs a discomfort"*, and *"I felt more immersed without the mirror"*. The possibility to look to one's own avatar motions in the mirror could have increased the chances to detect imperfections of the avatar control scheme. Also, the fact that we used inverse kinematics to animate the upper body of the avatar might have induced a lack of accuracy at the origin of those results.

Unlike the sense of ownership, to our knowledge the sense of agency had not yet been studied in relation to the presence or not of a mirror in virtual reality. For instance, while Slater et al. [40] explored the influence on agency of synchronous or asynchronous mirror reflections in IVR, they did not compare it to a control case without a mirror. Yet their results appeared to be in conflict with previous studies that suggested the importance of motor cues for the sense of self [13]. While our results suggest differences in the agency scores between the mirror and single conditions, such differences were small, showing the need to ensure accurate avatar control to maximize the sense of agency.

4.4 Limitations and Future Works

One of our verified hypotheses was that competition has an impact on user performance, showing an increase in user engagement. Indeed, the wack-a-mole task had a clear competitive dimension, which had for consequence that users were more attentive and efficient. However, the increase in engagement could have reduced the awareness of participants about their virtual body. Thus, it would be interesting to consider other tasks, reducing the ambiguity between engagement and embodiment. For instance, relevant tasks could involve higher awareness of one's virtual body and of others, such as users collaborating to achieve common goals while finely controlling their virtual body.

In addition, the interaction capabilities of the task were strongly constrained. For example, a participant reported that remaining seated, without being able to explore the room, reduced the ability of considering the virtual office as an actual real room. Further studies could explore increasing the interaction capabilities by providing the possibility to walk/navigate, or to interact with a wider range of virtual objects. Our results are also limited by the fact that we used only male participants, and further studies could be conducted using cross-gender or female participants. Finally, another aspect that requires additional research is the fact that we chose to have users sharing both the same virtual and physical environment. This implied that users eventually saw each other physically and could potentially talk and hear each other directly, which could have introduced additional implications in terms of social interactions. Our study could also be extended by involving more than two users.

5 Conclusion

In this paper, we explored how sharing a virtual environment with another user could generate changes in the behaviour and the perception of the virtual experience such as influencing the sense of embodiment. Our results show that shared experiences increased user engagement and the sense of presence, which is supported by performance and subjective measurements. In addition, all experimental conditions generated a strong sense of embodiment. Taken together, our results lead the way for VR applications designers to identify the important features to consider in order to develop multi-user VE. It can now be taken as an established fact that if users are immersed embodied in respective avatars, their SoE remains quite high, and so does the quality of their experience. It is also well-known that VR finds a large public in the entertainment area, and that multi-user games are quite popular in the gaming community. It is therefore relevant in this area to consider the influence of the competitive dimension existing in these applications on users' quality of experience.

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